Integrated, Object-oriented Dynamics Modeling for Design, Trajectory Optimization, and Control of Legged Robots

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Abstract

The development of flexible, dynamic and autonomous (i.e. guided by external and internal sensor data) motions for quadrupedal and humanoid robots is still a challenging and mainly unsolved task. The dynamics of legged robots is characterized by a free-floating, tree-like multibody systems structure with a high number of degrees of freedom consisting of many links and many actuated joints. Due to the frequent changes of the contact situation during legged motion frequent changes in the dynamic model occur. This special structure can usually not be utilized for an efficient implementation when using general purpose MBS formalisms and tools. To cope with the high complexity of the MBS dynamics of legged robots model-based methods for real-time actuator control, for on- and off-line trajectory optimization, and for controller design specifically tailored to the *one* scenario of legged robots must be developed. For rapid and virtual prototyping a most desireable goal is not only to apply the same abstract dynamic model representations and mathematical models but also as many parts as possible of the same *program code* for evaluating legged robot dynamics during *all stages* of design, development, implementation and operation of a legged robot. To facilitate the investigation of new concepts of nonlinear model-based optimization and control methods also the sensitivities of the legged robot dynamics model with respect to its state variables and parameters are needed. The formalisms and tools applied at the same time have to cope with (i) the complex underlying mechanical model, characterized by many degrees of freedom, actuator dynamics, and interaction of the robot with its physi-

cal environment including time-varying contacts and collisions, (ii) the wide range of required numerical schemes, including kinematics, dynamics, sensitivity information, etc., (iii) efficient code generation which is particularly vital for on-line computations, and must rely on the power of dedicated (recursive) algorithms, and (iv) interaction of the computational model with the system it is running on, e. g., communication with sensors and actuators.

This paper discusses the development and application of object-oriented modeling and implementation techniques to achieve a representation of the mechanical model amenable to the various requirements by legged robots applications. This leads to a uniform, modular, and flexible code generation while reaping the performance of efficient domain-specific articulated body algorithms. Trajectory optimization studies of a 6-dof manipulator and 12-dof legged robots are presented as applications. It is shown how high-level specification of multibody dynamics models using component libraries serves as a basis for generation of a number of modules forming an "overall" computational dynamics model. The selected examples illustrate how one copes with the emerging complexity by integrating various modules for, i. e., equations of motion, non-linear boundary conditions, symmetry and transition conditions, for multiple phases during motion. Variations of the mechanical structure, e. g., contact conditions can be treated either by multiple models or by reconfiguration of one model. Exact sensitivities, already developed and implemented for systems without contact, are used to improve the numerical convergence behaviour of the optimization method during differentiable phases. Numerical results are presented for time- and energy-optimal trajectories of full three-dimensional models of a standard six axes manufacturing robot, a 17 dof humanoid robot, and a Sony four-legged robot.

References

[1] M. Hardt and O. von Stryk, "Dynamic modeling in the simulation, optimization, and control of bipedal and quadrupedal robots", Zeitschrift für Angewandte Mathematik und Mechanik, vol. 83, no. 10, pp. 648-662, 2003.

[2] R. Höpler and P.J. Mosterman, "Model integrated computing in robot control to synthesize real-time embedded code", in *Proc. IEEE Conference on Control Applications*, Mexico City, pp. 767-772, 2001.

[3] M. Stelzer, M. Hardt and O. von Stryk, "Efficient dynamic modeling, numerical optimal control and experimental results for various gaits of a quadruped robot", in *Proc. CLAWAR 2003: International Conference on Climbing and Walking Robots*, Catania, Italy, September 17-19, 2003.